CHAPTER 1

THE ROLE OF THE OCEAN IN CLIMATE

Kevin Trenberth, Ph.D.
University Corporation for Atmospheric Research (UCAR)
Boulder, Colorado

a. The Role of the Ocean

The oceans cover about 71% of the Earth's surface and contain 97% of the Earth's water. Through their fluid motions, their high heat capacity, and their ecosystems, the oceans play a central role in shaping the Earth's climate and its variability. Changes in sea level have major impacts on coastal regions. Accordingly, it is vital to monitor and understand changes in the oceans and their effects on climate, and improve the quality of model ocean simulations. Much of the following is adapted from Trenberth (2001).

The most important characteristic of the oceans is that they are wet and, while obvious, this is sometimes overlooked. Water vapor, evaporated from the ocean surface, provides latent heat energy to the atmosphere during the precipitation process. In units of 1,000 km^3 per year, evaporation E over the oceans (436) exceeds precipitation P (399), leaving a net of 37 units of moisture transported onto land as water vapor. On average, this flow must be balanced by a return flow over and beneath the ground through river and stream flows, and subsurface ground water flow. The average precipitation rate over the oceans exceeds that over land by 72% (allowing for the differences in areas), and precipitation exceeds evapotranspiration over land by this same amount (37) (Dai and Trenberth 2002). This flow into the oceans occurs mainly in river mouths and is a substantial factor in the salinity of the oceans, thus affecting ocean density and currents. A simple calculation of the volume of the oceans of about 1330×10^6 km^3 and the through-flow fluxes of E and P implies an average residence time of water in the ocean of over 3,000 years.

Changes in phase of water, from ice to liquid to water vapor, affect the storage of heat. However, even ignoring these complexities, many facets of the climate can be deduced simply by considering the heat capacity of the different components of the climate system. The total heat capacity depends on the mass of the substance involved as well as its capacity for holding heat, as measured by the specific heat (the amount of heat needed to raise the temperature of one gram of a substance by 1°C), of each substance.

The atmosphere does not have much capability to store heat. The heat capacity of the global atmosphere corresponds to that of only a 3.2 m layer of the ocean. However, the depth of ocean actively involved in climate is much greater than that. The specific heat of dry land is roughly a factor of 4.5 less than that of seawater (for moist land the factor is probably closer to 2). Moreover, heat penetration into land is limited by the low thermal conductivity (the degree to which a substance transmits heat), of the land surface; as a result only the top two meters or so of the land typically play an active role in heat storage and release (e.g., as the depth for most of the variations over annual time scales). Accordingly, land plays a much smaller role than the ocean in the storage of heat and in providing a memory for the climate system. Major ice sheets, like those over Antarctica and Greenland, have a large mass but, like land, the penetration of heat occurs primarily through conduction (molecular transfer of energy due to a temperature gradient), so that the mass experiencing temperature changes from year to year is small. Hence, ice sheets and glaciers do not play a strong role in heat capacity, while sea ice is important where it forms.

The seasonal variations in heating penetrate into the ocean through a combination of radiation, convective overturning (in which cooled surface waters sink while warmer more buoyant waters below rise) and mechanical stirring by winds. These processes mix heat through the mixed layer, which, on average, involves about the upper 90 m of ocean. The thermal inertia of a 90 m layer can add a delay of about 6 years to the temperature response to an instantaneous change (this time corresponds to an exponential time constant in which there is a 63% response toward a new equilibrium value following an abrupt change). As a result, actual changes in climate tend to be gradual. With its mean depth of about 3800 m, the total ocean would add a delay of 230 years to the response if rapidly mixed. However, mixing is not a rapid process for most of the ocean so that in reality the response depends on the rate of ventilation of water between the well-mixed upper layers of the ocean and the deeper, more isolated layers that are separated by the thermocline (the ocean layer exhibiting a strong vertical temperature gradient). The rate of such mixing is not well established and varies greatly geographically. An overall estimate of the delay in surface temperature response caused by the oceans is 10–100 years. The slowest response should be in high latitudes where deep mixing and convection occur, and the fastest response is expected in the tropics. Consequently, the oceans are a great moderating effect on climate changes.

Wind blowing on the sea surface drives the large-scale ocean circulation in its upper layers. The oceans can move heat around through convection and advection (in which the heat is carried by the currents, whether small-scale short-lived eddies or large-scale currents). Hence, ocean currents carry heat and salt along with the fresh water around the globe. The oceans therefore store heat, absorbed at the surface, for varying durations and release it in different places; thereby ameliorating temperature changes over nearby land and contributing substantially to variability of climate on many time scales.

The ocean thermohaline circulation (THC), which is the circulation driven by changes in sea water density arising from temperature (thermal) or salt (haline) effects, allows water from the surface to be carried into the deep ocean, where it is isolated from atmospheric influence and hence it may sequester heat for periods of a thousand years or more. The oceans also absorb carbon dioxide and other gases and exchange them with the atmosphere in ways that change with ocean circulation and climate change. In addition, it is likely that marine biotic responses to climate change will result in subsequent changes that may have further ramifications.

b. An example: The annual cycle

In the subtropics, the oceans typically take up in excess of 100 W m^{-2} in the winter months and give it to the atmosphere in summer mostly in the form of evaporation of moisture. This cools the ocean while eventually warming the atmosphere when released as latent heat in precipitation (Trenberth and Stepaniak 2003). In mid-latitudes, air coming off the ocean is warmer than the land in winter and cooler in summer, giving rise to refreshing sea breezes and moderating temperatures. Regions influenced by the ocean in this way are referred to as having maritime climates.

An example of the role of the oceans in moderating temperature variations is the contrast in the mean annual cycle of surface temperature between the northern hemisphere (NH) (60.7% water) and southern hemisphere (SH) (80.9% water). The amplitude of the 12-month cycle between 40° and 60° latitude ranges from <3°C in the SH to about 12°C in the NH. Similarly, in mid-latitudes from 22.5°– 67.5° latitude, the average lag in temperature response relative to peak solar radiation is 32.9 days in the NH versus 43.5 days in the SH (Trenberth 1983), reflecting the differences in thermal inertia.

c. The oceans and sea ice

Sea ice is an active component of the climate system and varies greatly in areal extent with the seasons, but only at higher latitudes. In the Arctic where sea ice is confined by the surrounding continents, mean sea ice thickness is 3–4 m thick and multi-year ice can be present. Around Antarctica the sea ice is unimpeded and spreads out extensively, but as a result the mean thickness is typically 1–2 m. Sea ice caps the ocean and interferes with ocean-atmosphere exchanges of heat, moisture, and other gases. Melting sea ice freshens the ocean and diminishes the density. However, its greatest impact is through changes in albedo of the surface, the much darker ocean surface absorbs more solar radiation, further warming the ocean and leads to the ice-albedo positive feedback that amplifies initial perturbations. Diminished sea ice also increases moisture fluxes into the atmosphere, which may increase fog and low cloud, adding further complexity to the net albedo change. Ocean currents transport sea ice, which is also subject to stresses from surface wind.

d. Coupled ocean-atmosphere interactions

Understanding the climate system becomes more complex as the components interact. El Niño events are a striking example of a phenomenon that would not occur without interactions between the atmosphere and ocean. El Niño events involve a warming of the surface waters of the tropical Pacific. Ocean warming takes place from the International Dateline to the west coast of South America and results in changes in the local and regional ecology. Historically, El Niño events have occurred about every 3–7 years and alternated with the opposite phases of below average temperatures in the tropical Pacific, dubbed La Niña. In the atmosphere, a pattern of change called the Southern Oscillation is closely linked with these ocean changes, so that scientists refer to the total phenomenon as ENSO. Then El Niño is the warm phase of ENSO and La Niña is the cold phase.

The strong sea surface temperature (SST) gradient from the warm pool in the western tropical Pacific to the cold tongue in the eastern equatorial Pacific is maintained by the westward-flowing trade winds, which drive the surface ocean currents and determine the pattern of upwelling of cold nutrient-rich waters in the east. Because of the Earth's rotation, easterly winds along the equator deflect currents to the right in the NH and to the left in the SH and thus away from the equator, creating upwelling along the equator. Low sea level pressures are set up over the warmer waters while higher pressures occur over the cooler regions in the tropics and subtropics. The moisture-laden winds tend to blow toward low pressure so that the air converges, resulting in organized patterns of heavy rainfall and a large-scale overturning along the equator called the Walker Circulation. Because convection and thunderstorms preferentially occur over warmer waters, the pattern of SSTs determines the distribution of rainfall in the tropics, and this in turn determines the atmospheric heating patterns through the release of latent heat. The heating drives the large-scale overturning circulations in the tropics, and consequently determines the winds. If the Pacific trade winds relax, the ocean currents and upwelling change, causing temperatures to increase in the east, which decreases the surface pressure and temperature gradients along the equator, and so reduces the winds further. This positive feedback leads to the El Niño warming persisting for a year or so, but the ocean changes also sow the seeds of the event's demise. The changes in the ocean currents and internal waves in the ocean lead to a progression of colder waters from the west that may terminate the El Niño and lead to the cold phase, La Niña, in the tropical Pacific. The El Niño develops as a coupled ocean–atmosphere phenomenon and, because the amount of warm water in the tropics is redistributed, depleted and restored during an ENSO cycle, a major part of the onset and evolution of the events is determined by the history of what has occurred one to two years previously. This means that the future evolution is potentially predictable for several seasons in advance.

e. Sea level

Another major role of oceans in climate that has major impacts on multi-decadal time-scales is sea level rise. Climate models estimate that there is a current radiative imbalance at the top-of-the-atmosphere of about 7 W m^{-2} owing to increases of greenhouse gases, notably carbon dioxide, in the atmosphere. This has increased from a very small imbalance only 40 years ago. Where is this heat going? Some heat melts glaciers and ice, contributing to sea level rise. However, the main candidate for a heat sink is the oceans, leading to thermal expansion and further sea level rise. Levitus et al. (2000) have estimated that the heat content of the oceans has increased on average at a rate of about 3 W m^{-2} over the past few decades.

Sea level has risen throughout the twentieth century by 1.5±0.5 mm/year (IPCC 2001) but the rate appears to have accelerated in the 1990s when accurate global measurements of sea level from TOPEX/POSEIDEN altimetry became available. Recent estimates of sea level rise are 3.0 mm/year for 1993-2002 (Cazenave 2003, personal communication; and see Cabanes et al. 2001). To quote a recent assessment by Anny Cazenave (personal communication 2003) "During the 1990s, observed sea level rise is totally explained by thermal expansion. However, there is strong observational evidence for a significant eustatic contribution" of order 1 mm/yr. That is to say that melting of glaciers and ice sheets have added mass to the oceans at this rate (see e.g., Meier and Dyurgerov 2002). Estimates of other contributions (e.g., Cazenave et al. 2000) find that increased storage of water on land in reservoirs and dams accounts for –1.0±0.2 mm/yr; irrigation accounts for another –0.56±0.06 mm/yr but these are compensated for by ground water mining, urbanization, and deforestation effects so that the net sum of land effects is –0.9±0.5 mm/yr. Other small contributions also exist but there has been a reasonable accounting for the observed changes. Nevertheless, controversy remains about longer-term sea level rise (Munk 2003) and there is evidence of bias in the historical sea level station network (Cabanes et al. 2001). The so-called steric contribution from thermal expansion is based mostly on the analysis of the historical record of Levitus et al. (2001). Yet that record is based on sub-surface ocean measurements which are inadequate in many areas, for instance little or no sampling over many parts of the southern oceans to even determine the mean, let alone the variations with time. Future sea level rise, and whether or not the rate is increasing are vital issues for climate change and impacts on small island states and coastal regions.

f. Why are we observing the ocean?

The above describes the critical role of the oceans in climate. Oceans take up heat in the summer half year and release it in winter, playing a major role in moderating climate. The oceans play a crucial role in ENSO. However, the enormous heat capacity of the oceans means that the oceans also play a key role on decadal and longer timescales. The exact role of the oceans in the North Atlantic Oscillation (the predominant mode of atmospheric variability in the Northern Hemisphere in winter that relates to the strength of the hemispheric-scale westerly flow) is being explored. Variations in the ocean affect ecosystems, including fisheries, which are of direct importance for food and the economy. It is therefore important to track the changes in ocean heat storage, as well as the uptake and release of heat in the oceans through the surface fluxes.

Salinity effects on ocean density are also important but are poorly measured at present. It is essential to be able to attribute changes in ocean heat content and the mass of the ocean to causes (such as changing atmospheric composition), perhaps using models. Climate models suggest that the THC could slow down as global warming progresses, resulting in counter-intuitive relative regional cooling or, more likely, reduced warming on multi-decadal time-scales.

It is vital to establish a baseline of the current state of the ocean as a reference for future assessments. Monitoring of the top 500 m of the near-equatorial Pacific Ocean has been established because of ENSO. It is an excellent start. The Tropical Oceans Global Atmosphere (TOGA) program and World Ocean Circulation Experiment (WOCE) have paved the way. Increasing attention will be devoted to measurements of the biogeochemistry of the oceans and especially the carbon cycle, and possible feedbacks on carbon dioxide levels in the atmosphere. Relationships of physical ocean changes to ecosystems and fish stocks will enable improved fishery management. Observing technologies are evolving, and plans are already underway for an initial ocean observing system, but it has yet to be fully implemented. The observing system must evolve in ways that protects the integrity and continuity of the climate record. Such a system must be linked to comprehensive analysis capabilities of not only the ocean, but also the atmosphere, sea ice, radiation, precipitation, and other ingredients in the climate system. From time to time it is expected that reanalyses of the past ocean and climate record will be desirable as improvements are made in models and data assimilation systems. Tracking the performance of the observing system to ensure that it is meeting needs is another necessary component (Trenberth et al. 2002). With such information, and good models, we will be enabled to make skilful predictions of climate on timescales ranging from weeks, to interannual (ENSO), to decades. However, good ocean observations are also essential for developing better models.

Ongoing assessments are therefore required of the continually changing state of the ocean, as well as our ability to observe it and assess what is going on. It is therefore appropriate for NOAA to carry out an annual assessment of both the state of the ocean and the state of the observing system, examine how well needs are being met, and find timely remedies for inadequacies.

References

Cabanes, C., A. Cazenave, and C. Le Provost, Sea level rise during past 40 years determined from satellite and *in situ* observations, *Science*, *294*, 840-842, 2001.

Cazenave A., F. Remy, K. Dominh and H. Douville, Global ocean mass variation, continental hydrology and the mass balance of the Antarctica ice sheet at the seasonal time scale, *Geophysical Research Letters, 27*, 3755-3758, 2000.

Dai, A., and K. E. Trenberth, Estimates of freshwater discharge from continents: Latitudinal and seasonal variations, *Journal of Hydrometeorology*, *3,* 660–687, 2002.

IPCC (Intergovernmental Panel on Climate Change), *Climate Change 2001. The scientific basis*. Eds. J. T. Houghton, et al. Cambridge University Press, Cambridge, U.K. 881pp., 2001.

Levitus, S., J. I. Antonov, T. P Boyer, and C. Stephens, Warming of the world ocean, *Science, 287,* 2225-2229, 2000.

Levitus, S., J. I. Antonov, J. Wang, T. L. Delworth, K. W. Dixon, and A. J. Broccoli, Anthropogenic warming of earth's climate system, *Science*, *292*, 267-270, 2001.

Meier, M. F., and M. B. Byurgerov, How Alaska affects the world, *Science*, *297*, 350-351, 2002.

Munk, W., Ocean freshening, sea level rising, *Science*, *300*, 2041-2043, 2003.

Trenberth, K. E., What are the seasons?, *Bulletin of the American Meteorological Society*, *64*, 1276–1282, 1983.

Trenberth, K. E., Earth System Processes, *Encyclopedia of Global Environmental Change*, T. Munn (Ed. in Chief), Vol. 1. The Earth System: Physical and Chemical Dimensions of Global Environmental Change, M. C. MacCracken and J. S. Perry (Eds), John Wiley & Sons Ltd., 13–30, 2001.

Trenberth, K. E., T. R. Karl and T. W. Spence, The need for a systems approach to climate observations, *Bulletin of the American Meteorological Society*, *83*, 1593–1602 2002.

Trenberth, K. E., and D. P. Stepaniak, Seamless poleward atmospheric energy transports and implications for the Hadley circulation, *Journal of Climate*, *16*, 3705–3721, 2003.